AlGaAs Photovoltaics for Indoor Energy Harvesting in mm-Scale Wireless Sensor Nodes

Alan S. Teran, *Student Member, IEEE*, Joeson Wong, *Student Member, IEEE*, Wootaek Lim, *Student Member, IEEE*, Gyouho Kim, *Member, IEEE*, Yoonmyoung Lee, *Member, IEEE*, David Blaauw, *Fellow, IEEE*, and Jamie D. Phillips, *Senior Member, IEEE*

***Abstract*— Indoor photovoltaic energy harvesting is a promising candidate to power millimeter (mm)-scale systems. The theoretical efficiency and electrical performance of photovoltaics under typical indoor lighting conditions are analyzed. Commercial crystalline Si and fabricated GaAs and $Al_{0.2}Ga_{0.8}As$ photovoltaic cells were experimentally measured under simulated AM 1.5 solar irradiation and indoor illumination conditions using a white phosphor light-emitting diode to study the effects of input spectra and illuminance on performance. The $Al_{0.2}Ga_{0.8}As$ cells demonstrated the highest performance with a power conversion efficiency of 21%, with open-circuit voltages >0.65 V under low lighting conditions. The GaAs and $Al_{0.2}Ga_{0.8}As$ cells each provide a power density of ∼100 nW/mm^2 or more at 250 lx, sufficient for the perpetual operation of present-day low-power mm-scale wireless sensor nodes.**

***Index Terms*— Aluminum gallium arsenide (AlGaAs), energy harvesting, gallium arsenide (GaAs), photovoltaics.**

I. Introduction

LOW-POWER electronic circuitry, including wirelessly interconnected sensor nodes, offers a transformational technology that can enable unsurpassed interconnectivity and a paradigm shift known as the Internet of Things or Internet of Everything. These low-power systems require a source of energy, ideally from ambient sources. Ambient indoor lighting can provide sufficient energy for most of these applications, with a power density of ∼1 μW/mm^2 under dim lighting conditions. Energy-autonomous operation of millimeter (mm)-scale sensors has been previously achieved using photovoltaic cells based on silicon CMOS [1]–[3]. The power requirements for mm-scale computers under active and standby operation are ∼10 W and 0.5 nW, respectively [1]–[4]. Sunlight is more than adequate, providing 1 mW/mm^2 of power under full sun, or ∼100 μW/mm^2 for a conversion efficiency of 10%. However, stray sunlight is not available in all locations, or at all times. Indoor lighting may also provide sufficient energy, though the intensity and spectral content are significantly different than sunlight. Today, efficient indoor lighting sources, such as light-emitting diodes (LEDs) and fluorescent lamps, provide a relatively narrow band of light in the visible spectral region with a power density on the order of 1 μW/mm^2 (for the illuminance of ∼600 lx).

The optical spectrum for indoor lighting is primarily contained in a narrow spectral band in the visible region. The spectrum can also vary depending on the light source (e.g., incandescent, fluorescent, and LED) and color rendering (e.g., warm white and cool white). Fluorescent and LED lighting, in particular, have similar spectral content such that the photovoltaic response will be very similar in both cases. The optimal bandgap energy for a photovoltaic cell for indoor lighting will correspond to the edge of the visible spectrum, and will be larger than the optimal bandgap energy for solar illumination due to the absence of spectral content beyond the visible region. The larger bandgap energy will provide a larger voltage output while also absorbing the full spectrum provided from indoor lighting. Silicon, with bandgap energy of 1.1 eV corresponding to the IR spectral region, is, therefore, smaller than desired for efficient energy harvesting under indoor lighting conditions. Alternatively, III–V compound semiconductor materials, such as GaAs, provide larger bandgap energy with proven high conversion efficiency and a wide range of accessible spectral windows. While the cost of photovoltaics based on III–V semiconductors is significantly higher than for silicon, and is currently prohibitive for large area solar energy production, the small power requirements and associated size requirements for indoor photovoltaic cells make these materials an affordable option for indoor applications.

Studies of indoor photovoltaics have been reported previously using various technologies, including crystalline silicon [5]–[18], amorphous silicon [5]–[8], [12], [14], [15], [18]–[20], GaAs [5]–[7], [14], [21], InGaP, CdTe [5]–[7], [14], [15], [18], copper indium gallium diselenide [5]–[8], [14], [22], organic [15], [18], [22], and dye-sensitized cells [5]–[7], [15], [18], [22]. Theoretical calculations suggest an optimal bandgap energy of 1.9–2 eV for indoor lighting sources

Manuscript received February 25, 2015; revised April 22, 2015 and May 11, 2015; accepted May 14, 2015. Date of publication June 1, 2015; date of current version June 17, 2015. This work was supported by the National Science Foundation under Grant DMR-1006154. The review of this paper was arranged by Editor A. G. Aberle.

A. S. Teran, J. Wong, W. Lim, G. Kim, D. Blaauw, and J. D. Phillips are with the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109 USA (e-mail: asteran@umich.edu; joesonw@umich.edu; imhotep@umich.edu; gyouhokim@umich.edu; blaauw@umich.edu; jphilli@umich.edu).

Y. Lee is with the Department of Semiconductor Systems Engineering, Sungkyunkwan University, Suwan 440-746, Korea (e-mail: yoonmyung@skku.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TED.2015.2434336

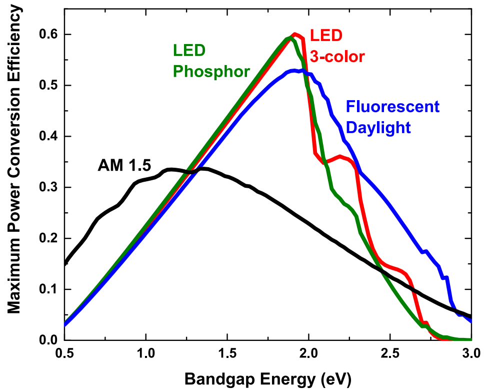

Fig. 1. Calculated maximum power conversion efficiency versus material bandgap energy under various lighting sources revealing an ideal bandgap energy near 1.9 eV for indoor conditions.

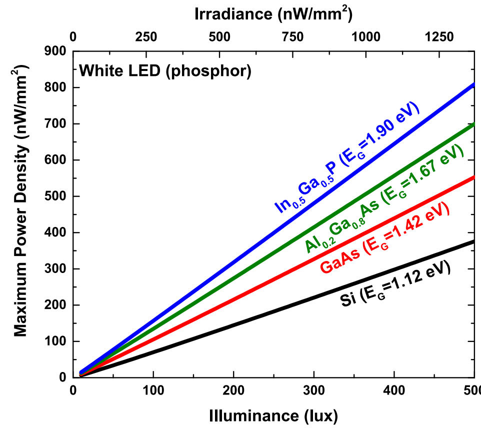

Fig. 2. Calculated maximum power density versus illuminance for select materials under white phosphor LED illumination, illustrating that target goals of >100 nW in a 1 mm^2 area may be reasonably achieved.

[15], [18] in comparison with the Shockley–Queisser limit of 1.34 eV for AM 1.5 solar illumination [23]. However, the dependence of efficiency on lighting intensity, and ultimate energy/power harvesting for mm-scale systems has not been established. In addition to the bandgap energy of the material, which governs the fundamental absorption properties, output voltage, and dark current limitations, the parallel (shunt) resistance for a photovoltaic cell will have strong influence on performance under low-light conditions [5]–[9], [14], [15], [18]. In this paper, the efficiency and power density limits for energy harvesting under indoor lighting conditions are evaluated, with particular emphasis on the dependence of performance on bandgap energy and illuminance. The design and experimental performance of gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs) photovoltaic cells are reported under indoor lighting conditions and compared with crystalline silicon.

II. Efficiency and Power Density Limits

Maximum energy harvesting under indoor lighting conditions was calculated based on detailed balance theory assuming photovoltaic cells with full optical absorption for energy above the material bandgap, radiatively limited performance, and full collection of charge carriers. Three indoor lighting spectra were considered: 1) fluorescent source with daylight color rendering; 2) LED with phosphor; and 3) three-color LED, with spectra given in [24]–[26]. The resulting efficiency values versus bandgap energy are shown in Fig. 1, comparing the AM 1.5 solar spectrum and various indoor lighting sources with 500 lx intensity. It should be noted that indoor lighting intensity is typically reported in photometric units of lumens or lux, rather than radiometric units of watts or watts per unit area, respectively. Lighting conditions will be described in terms of lux throughout while also providing corresponding values of radiometric power density for comparison with values typically quoted for solar photovoltaics. Of the three spectra, the maximum efficiency can be obtained for a three-color LED corresponding to bandgap energy of 1.9 eV and efficiency of 60%. Analysis to compare limiting efficiencies with variable indoor lighting sources has similarly been conducted in [15], where an optimal bandgap energy of 1.9–2 eV was determined. Higher efficiency may be obtained for indoor lighting sources in comparison with sunlight, since the narrower spectral band mitigates transparency losses and thermalization losses associated with the broadband solar spectrum. It should be noted that the conversion efficiency near the peak is relatively independent of the indoor lighting source. While higher conversion efficiency may ultimately be achieved for indoor lighting relative to sunlight, the actual light intensity is significantly lower (1–2 W/m^2). $In_{0.5}Ga_{0.5}P$ has a bandgap energy of 1.9 eV, matching the ideal for indoor photovoltaics. Studies have shown an experimental maximum efficiency under fluorescent lighting of 16% using InGaP photovoltaic cells [15], [18].

The dependence of power density on indoor lighting illuminance is perhaps the most relevant figure for mm-scale systems. A comparison of maximum achievable power density versus illuminance for select bandgap energies is shown in Fig. 2. For these relatively standard indoor lighting conditions, a power density >100 nW/mm^2 can be obtained. The analysis also underscores the large improvements in energy harvesting that may be achieved by considering materials with larger bandgap energy than silicon. The analysis described assumes perfect optical absorption and carrier collection, and does not consider material-specific parameters and how they would influence device design and conversion efficiency.

III. Experimental Results

The influence of the indoor lighting spectrum on photovoltaic energy conversion efficiency was investigated experimentally for materials with varying bandgap energy, including commercial crystalline silicon [27], GaAs, and $Al_{0.2}Ga_{0.8}As$ photovoltaic cells. The commercial Si cell used in this paper was chosen based on the availability of a single-junction cell intended for the application of powering small-scale electronics. The Si cell had an active area of 154 mm^2, while the fabricated GaAs and $Al_{0.2}Ga_{0.8}As$ cells had an active area of 1 mm^2. GaAs cell design and fabrication has been reported in [28], where the $Al_{0.2}Ga_{0.8}As$ photovoltaic cells had

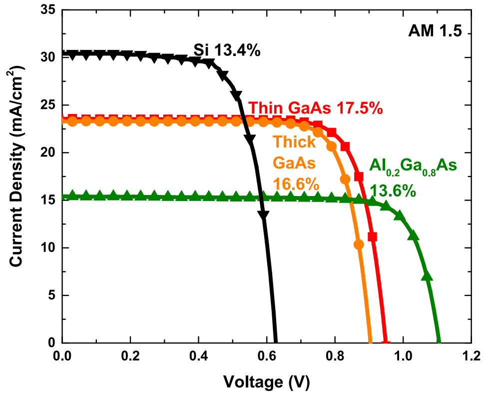

Fig. 3. Photovoltaic response for various cell designs under AM 1.5 illumination.

a similar design, but with the addition of Al to the emitter and base layers. The effects of absorber thickness were investigated using two GaAs cells with different base thickness. The thick cell had a base layer thickness of 3 μm with a doping level of 1×10^{17} cm^{-3}, while the thin cell had a base layer thickness of 0.7 μm with a doping level of 5×10^{17} cm^{-3}.

The electrical performance of all four photovoltaic cells was measured under both the simulated AM 1.5 solar spectrum and indoor lighting conditions using a white phosphor LED. All of the measurements were performed at room temperature. The results under one-sun illumination are shown in Fig. 3. The fabricated GaAs-based cells outperformed the commercial Si solar cell with power conversion efficiencies of 17.5%, 16.6%, and 13.6% for the thin GaAs, thick GaAs, and $Al_{0.2}Ga_{0.8}As$, respectively. The commercial Si solar cell had a comparable efficiency of 13.4%. While these photovoltaic cells are by no means representative of record power conversion efficiency, they possess respectable efficiencies that may be used for qualitative comparison purposes.

The $Al_{0.2}Ga_{0.8}As$ cell performed the best when illuminated with a white phosphor LED, as shown in Fig. 4(a). Maximum power densities >100 nW/mm^2 were achieved under typical indoor lighting conditions (580 lx), as shown in Fig. 4(b). Under these conditions, the $Al_{0.2}Ga_{0.8}As$ cell had the highest power conversion efficiency of 21.1%. To the best of our knowledge, this is the highest reported photovoltaic power conversion efficiency for indoor lighting. The thin GaAs, thick GaAs, and Si cells demonstrated the power conversion efficiency values of 19.4%, 15.5%, and 5.2%, respectively, under LED illumination at 580 lx. The efficiency values were calculated using measured luminous efficacy of radiation of the white phosphor LED used for these measurements. The spectral characteristics of the white phosphor LED is shown in Fig. 5 along with the luminosity function. The luminous efficacy of radiation is calculated by taking the inner product of the irradiance and luminosity function resulting in a value of 420 lm/W for the LED used in these experiments.

The maximum power density versus illuminance is shown in Fig. 6. Under extremely dim lighting conditions (<100 lx), the GaAs-based photovoltaic cells achieved power densities >10 nW/mm^2. The commercial Si solar cell required illuminance of >150 lx to provide a power density of >10 nW/mm^2.

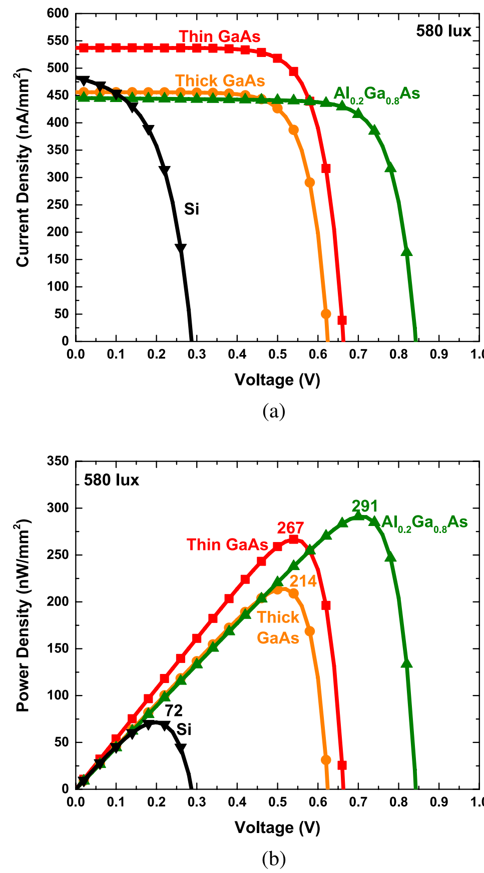

Fig. 4. Measured (a) current density versus voltage and (b) power density versus voltage of $Al_{0.2}Ga_{0.8}As$ and two differing GaAs cell designs measured under white LED illumination and comparison with a commercial silicon solar cell.

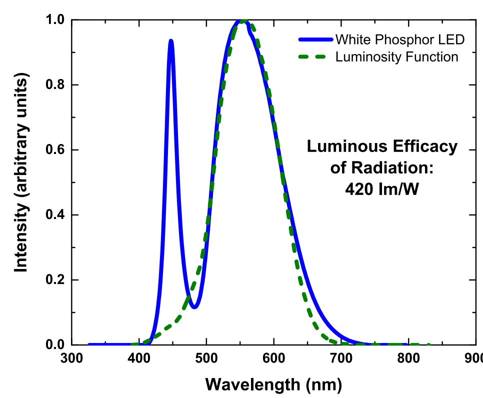

Fig. 5. Measured spectral content of the white phosphor LED used and luminosity function. The luminous efficacy of radiation is calculated by taking the inner product of the irradiance and luminosity function.

A power density of 10 nW/mm^2 represents an approximate target value for perpetual operation of mm-scale systems, which can be achieved for illuminance of ~100 lx or higher in the cells studied in this paper.

The importance of cell performance at low illuminance is illustrated by the dependence of open-circuit voltage (V_{OC}) and fill factor on illumination, as shown in Fig. 7. For a drop in illuminance from 1000 to 20 lx, the $Al_{0.2}Ga_{0.8}As$, thin GaAs,

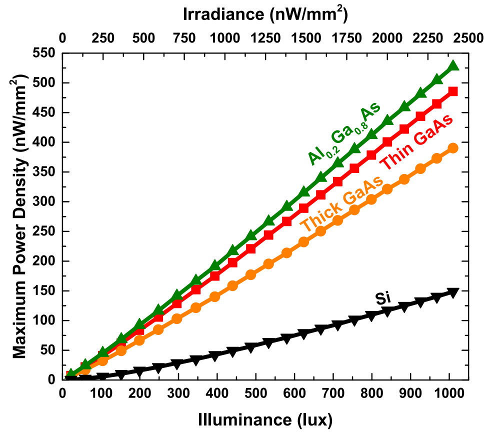

Fig. 6. Measured maximum power density versus illuminance of $Al_{0.2}Ga_{0.8}As$ and two differing GaAs cell designs measured under white LED illumination and comparison with a commercial silicon solar cell.

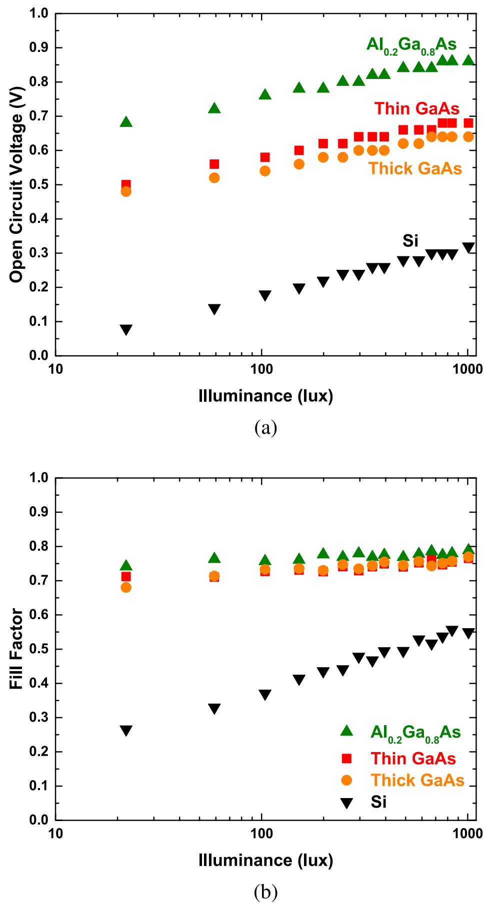

Fig. 7. (a) Open-circuit voltage and (b) fill factor versus illuminance of $Al_{0.2}Ga_{0.8}As$ and two differing GaAs cell designs measured under white LED illumination and comparison with a commercial silicon solar cell illustrating V_{OC} and fill-factor degradation at low illumination due to dark current and shunt leakage.

and thick GaAs photovoltaic cells exhibit a decrease in V_{OC} of 21%, 26%, and 25% along with a decrease in fill factor of 6%, 7%, and 12%, respectively. In comparison, the commercial Si solar cell suffers a 75% decrease in V_{OC} and a 52% decrease in fill factor.

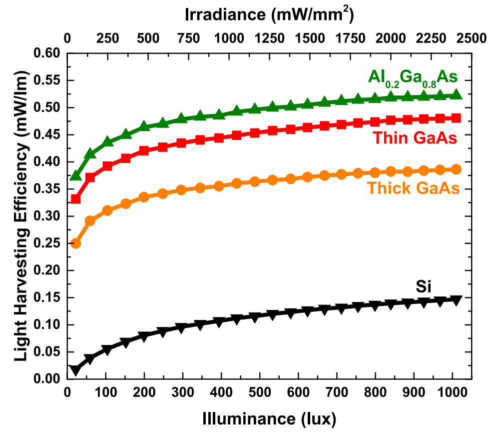

Fig. 8. Measured LHE versus illuminance of $Al_{0.2}Ga_{0.8}As$ and two differing GaAs cell designs measured under white LED illumination and comparison with a commercial silicon solar cell.

IV. Discussion

Under typical indoor lighting conditions, the GaAs-based photovoltaic cells outperformed the commercial crystalline Si solar cell, where there is a dramatic decrease in fill factor and efficiency for the crystalline Si cell for indoor lighting in comparison with one-sun illumination. The four photovoltaic cells demonstrated a relatively similar short-circuit current (J_{SC}) under indoor conditions relative to AM 1.5 illumination, with some degree of variability related to optical absorption and carrier collection. However, the V_{OC} varies dramatically, following the trend of decreasing V_{OC} with material bandgap energy. The $Al_{0.2}Ga_{0.8}As$ cell delivered the highest maximum power density and power conversion efficiency primarily due to the larger bandgap energy of the absorber material and similar fill factor to the GaAs cells. The thin GaAs cell outperformed the thick GaAs cell due to more efficient carrier collection and increased V_{OC} associated with the elevated doping concentration. The V_{OC} reduction of the crystalline silicon cell with respect to the one-sun condition is dramatically lower than expected based on the logarithmic relation with light intensity. Performance degradation under low-light conditions has similarly been reported for crystalline silicon, and attributed to parasitic shunt current leakage [5]–[9], [14], [15], [18], which is observed in the current silicon cell via the low fill factor, as shown in Figs. 4 and 7.

Light-harvesting efficiency (LHE) can be reported as standard radiometric power conversion efficiency, or more conveniently, as photometric power conversion efficiency in watt/lumen. These two are related by the luminous efficacy of the light source (420 lm/W in this paper). Continued study of photovoltaic indoor light harvesting should also include the development of standardized test conditions analogous to those developed for solar cells. An LHE of 0.1 mW/lm (4.6% power conversion efficiency) or greater would be able to power mm-scale sensors with photovoltaic cells of similar dimensions [1]–[4]. The experimental dependence of LHE on illuminance is shown in Fig. 8. The $Al_{0.2}Ga_{0.8}As$ cell has the highest LHE, followed by the thin GaAs cell, thick GaAs cell, and the commercial Si cell. Reduced cell efficiency at low illuminance can be attributed to either dark current or parasitic shunt current [5]–[9], [14], [15], [18]. The current density voltage relations for a diode photovoltaic cell are described by

$$J = J_L - J_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - \frac{V}{R_{SH}}$$

where J is the current density, J_L is the photogenerated current density, J_0 is the dark saturation current density, q is the electron charge, V is the voltage across the cell terminals, n is the diode ideality factor, k is the Boltzmanns constant, T is the temperature, and R_{SH} is the cell shunt resistance. Under sufficiently high illumination conditions, such as one-sun illumination, the current shunt represented by V/R_{SH} is negligible in comparison with the generated photocurrent, while the dark current is negligible for voltages significantly below V_{OC}. Under low illumination conditions, such as indoor lighting, the proportional decrease in J_L can become comparable with V/R_{SH} and J_0, resulting in a dramatic reduction in V_{OC}, fill factor, and subsequent LHE. Studies have shown a significant perimeter recombination effect in GaAs-based solar cells of large perimeter-to-area ratio (P/A) [29]–[31]. The perimeter recombination effect dominates the dark current component under low illumination, degrading fill factor. Such an effect is expected for the photovoltaic cells in this paper given their large P/A and the low illumination conditions during measurements.

Prior experimental results on photovoltaic cells exhibit a decrease in power conversion efficiency under the reduced intensity of indoor lighting conditions, despite the detailed balance predictions for higher efficiency associated with more efficient utilization of the narrow spectral band of indoor lighting relative to sunlight. The relatively low shunt resistance in crystalline silicon is well known, where materials with high parallel resistance, such as amorphous silicon and CdTe, have been shown to provide improved performance under low-light conditions despite reduced efficiency under one-sun conditions [5]–[8], [14], [15], [18]. However, a-Si and CdTe cells have thus far exhibited a net decrease in power conversion efficiency for indoor lighting with respect to AM 1.5 illumination. The AlGaAs and GaAs cells in this paper exhibit a substantial increase in power conversion efficiency under indoor lighting conditions, demonstrating a breakthrough for energy harvesting of indoor lighting. The measured power conversion efficiency for the GaAs and AlGaAs cells is still well below the theoretical detailed balance limit (∼50%), suggesting that there is still substantial opportunity for improvement. This result also underscores the importance of understanding mechanisms for dark current and shunt leakage in these devices and the dependence on material properties and device fabrication processes.

V. Conclusion

Perpetual operation of mm-scale systems that require an average power density of 10 nW/mm^2 can be achieved using photovoltaics by indoor light harvesting under typical conditions. A maximum theoretical power conversion efficiency of 60% can be achieved under typical indoor lighting by a semiconductor with 1.9-eV bandgap energy. Commercial Si and fabricated GaAs-based photovoltaic cells were measured under typical indoor lighting conditions, demonstrating LHE ∼0.1 and 0.5 mW/lm, respectively. While crystalline silicon cells exhibit a sharp degradation in efficiency at low illuminance, the GaAs, and $Al_{0.2}Ga_{0.8}As$ cells maintain high efficiency, which can be attributed to low dark current levels and relative insensitivity to shunt current leakage. The $Al_{0.2}Ga_{0.8}As$ cell demonstrated the highest reported indoor power conversion efficiency of 21%. The combination of high power conversion efficiency and insensitivity to low-illuminance conditions suggest that AlGaAs photovoltaics are highly promising for energy harvesting in mm-scale wireless sensor nodes.

References

[1] Y. Lee *et al.*, "A modular 1 mm^3 die-stacked sensing platform with low power I^{2}C inter-die communication and multi-modal energy harvesting," *IEEE J. Solid-State Circuits*, vol. 48, no. 1, pp. 229–243, Jan. 2013.

[2] M. Fojtik *et al.*, "A millimeter-scale energy-autonomous sensor system with stacked battery and solar cells," *IEEE J. Solid-State Circuits*, vol. 48, no. 3, pp. 801–813, Mar. 2013.

[3] W. Jung *et al.*, "An ultra-low power fully integrated energy harvester based on self-oscillating switched-capacitor voltage doubler," *IEEE J. Solid-State Circuits*, vol. 49, no. 12, pp. 2800–2811, Dec. 2014.

[4] S. Hanson *et al.*, "A low-voltage processor for sensing applications with picowatt standby mode," *IEEE J. Solid-State Circuits*, vol. 44, no. 4, pp. 1145–1155, Apr. 2009.

[5] J. F. Randall and J. Jacot, "The performance and modelling of 8 photovoltaic materials under variable light intensity and spectra," *World Renew. Energy Congr. VII Expo*, 2002.

[6] J. F. Randall and J. Jacot, "Is AM1.5 applicable in practice? Modelling eight photovoltaic materials with respect to light intensity and two spectra," *Renew. Energy*, vol. 28, no. 12, pp. 1851–1864, 2003.

[7] J. F. Randall, *Designing Indoor Solar Products: Photovoltaic Technologies for AES*. Chichester, U.K.: Wiley, 2005.

[8] N. H. Reich *et al.*, "Weak light performance and spectral response of different solar cell types," in *Proc. 20th Eur. Photovolt. Solar Energy Conf. Exhibit.*, 2005, pp. 6–10.

[9] G. E. Bunea, K. E. Wilson, Y. Meydbray, M. P. Campbell, and D. M. De Ceuster, "Low light performance of mono-crystalline silicon solar cells," in *Proc. IEEE 4th World Conf. Photovolt. Energy*, May 2006, pp. 1312–1314.

[10] A. Nasiri, S. A. Zabalawi, and G. Mandic, "Indoor power harvesting using photovoltaic cells for low-power applications," *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4502–4509, Nov. 2009.

[11] K. Rühle, S. W. Glunz, and M. Kasemann, "Towards new design rules for indoor photovoltaic cells," in *Proc. 38th IEEE Photovolt. Specialists Conf.*, Jun. 2012, pp. 2588–2591.

[12] K. Rühle, M. Freunek, L. M. Reindl, and M. Kasemann, "Designing photovoltaic cells for indoor energy harvesting systems," in *Proc. 9th Int. Multi-Conf. Syst., Signals, Devices*, Mar. 2012, pp. 1–5.

[13] K. Rühle *et al.*, "Passivation layers for indoor solar cells at low irradiation intensities," in *Proc. 2nd Int. Conf. Crystal. Silicon Photovolt.*, vol. 27. 2012, pp. 406–411.

[14] S. Beeby and N. White, *Energy Harvesting for Autonomous Systems*. Norwood, MA, USA: Artech House, 2010.

[15] M. Freunek, M. Freunek, and L. M. Reindl, "Maximum efficiencies of indoor photovoltaic devices," *IEEE J. Photovolt.*, vol. 3, no. 1, pp. 59–64, Jan. 2013.

[16] M. Kasemann, K. Rühle, K. M. Gad, and S. W. Glunz, "Photovoltaic energy harvesting for smart sensor systems," *Proc. SPIE, Smart Sens., Actuators, MEMS VI*, vol. 8763, p. 87631T, May 2013.

[17] K. Rühle and M. Kasemann, "Approaching high efficiency wide range silicon solar cells," in *Proc. 39th IEEE Photovolt. Specialists Conf.*, Jun. 2013, pp. 2651–2654.

[18] M. Freunek, "Indoor photovoltaics: Efficiencies, measurements and design," in *Solar Cell Nanotechnology*. Beverly, MA, USA: Scrivener Publishing, 2014, pp. 203–222.

[19] W. S. Wang, T. O'Donnell, L. Ribetto, B. O'Flynn, M. Hayes, and C. O'Mathuna, "Energy harvesting embedded wireless sensor system for building environment applications," in *Proc. 1st Int. Conf. Wireless Commun., Veh. Technol., Inf. Theory, Aerosp. Electron. Syst. Technol.*, May 2009, pp. 36–41.
[20] Y. K. Tan and S. K. Panda, "Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4424–4435, Sep. 2011.
[21] I. Mathews, G. Kelly, P. J. King, and R. Frizzell, "GaAs solar cells for indoor light harvesting," in *Proc. 40th IEEE Photovolt. Specialists Conf.*, Jun. 2014, pp. 510–513.
[22] A. Sacco, L. Rolle, L. Scaltrito, E. Tresso, and C. F. Pirri, "Characterization of photovoltaic modules for low-power indoor application," *Appl. Energy*, vol. 102, pp. 1295–1302, Feb. 2013.
[23] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *J. Appl. Phys.*, vol. 32, no. 3, pp. 510–519, 1961.
[24] Y. Ohno, "Color rendering and luminous efficacy of white LED spectra," in *Proc. SPIE, 4th Int. Conf. Solid State Lighting*, vol. 5530. 2004, pp. 88–98.
[25] Y. Ohno, "Spectral design considerations for white LED color rendering," *Opt. Eng.*, vol. 44, no. 11, pp. 111302-1–111302-9, 2005.
[26] W. Davis and Y. Ohno, "Toward an improved color rendering metric," in *Proc. SPIE, 5th Int. Conf. Solid State Lighting*, vol. 5941. 2005, p. 59411G.
[27] (2015). *IXYS IXOLAR SolarBIT KXOB22-12x1*. [Online]. Available: http://www.digikey.com/product-detail/en/KXOB22-12X1/KXOB22-12X1-ND/2754272
[28] J. Hwang, A. J. Martin, K. Lee, S. Forrest, J. Millunchick, and J. Phillips, "Preserving voltage and long wavelength photoresponse in GaSb/GaAs quantum dot solar cells," in *Proc. IEEE 39th Photovolt. Specialist Conf.*, Jun. 2013, pp. 3191–3194.
[29] P. D. DeMoulin, S. P. Tobin, M. S. Lundstrom, M. S. Carpenter, and M. R. Melloch, "Influence of perimeter recombination on high-efficiency GaAs p/n heteroface solar cells," *IEEE Electron Device Lett.*, vol. 9, no. 8, pp. 368–370, Aug. 1988.
[30] A. Belghachi and S. Khelifi, "Modelling of the perimeter recombination effect in GaAs-based micro-solar cell," *Solar Energy Mater. Solar Cells*, vol. 90, no. 1, pp. 1–14, 2006.
[31] P. Espinet-González, I. Rey-Stolle, M. Ochoa, C. Algora, I. García, and E. Barrigón, "Analysis of perimeter recombination in the subcells of GaInP/GaAs/Ge triple-junction solar cells," *Prog. Photovolt., Res. Appl.*, pp. 1–9, Apr. 2014.

Alan S. Teran (S'08) received the B.S. degree in electrical engineering from the University of Florida, Gainesville, FL, USA, in 2010. He is currently pursuing the Ph.D. degree with the University of Michigan, Ann Arbor, MI, USA.

His current research interests include intermediate band solar cells and indoor energy harvesting using photovoltaics.

Joeson Wong (S'14) received the B.S. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2015. He will be pursuing the Ph.D. degree in applied physics with the California Institute of Technology, Pasadena, CA, USA.

His current research interests include highly efficient solar concentrator modules and luminescent 2-D materials for photovoltaic applications.

Wootaek Lim (S'15) received the B.S. degree in electrical engineering from Seoul National University, Seoul, Korea, in 2013. He is currently pursuing the Ph.D. degree with the University of Michigan, Ann Arbor, MI, USA.

His current research interests include ultralow power mixed-signal systems and robust design methodologies.

Gyouho Kim (S'12–M'14) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2009, 2011, and 2014, respectively.

He is currently a Post-Doctoral Research Fellow with the University of Michigan. His current research interests include ultralow power very large scale integration design for energy-constrained systems.

Yoonmyoung Lee (S'08–M'12) received the B.S. degree in electronic and electrical engineering from the Pohang University of Science and Technology, Pohang, Korea, in 2004, and the M.S. and Ph.D. degrees from the University of Michigan, Ann Arbor, MI, USA, in 2008 and 2012, respectively.

He is currently an Assistant Professor with Sungkyunkwan University, Suwan, Korea.

David Blaauw (SM'07–F'12) received the B.S. degree in physics and computer science from Duke University, Durham, NC, USA, in 1986, and the Ph.D. degree in computer science from the University of Illinois at Urbana–Champaign, Urbana, IL, USA, in 1991.

He has been on the Faculty with the University of Michigan, Ann Arbor, MI, USA, since 2001, where he is currently a Professor.

Jamie D. Phillips (M'01–SM'06) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, MI, USA.

He was with Sandia National Laboratories, Livermore, CA, USA, and the Rockwell Science Center, San Diego, CA, USA, before returning to the University of Michigan, where he is currently an Arthur F. Thurnau Professor. His current research interests and contributions are in optoelectronic materials and devices.